COMBUSTION CHARACTERIZATION OF GTL DIESEL FUEL

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Introduction

Synthetic diesel fuel production from natural gas offers the potential of both monetizing stranded natural gas resources and providing a supply of ultra clean transportation fuels. Gas-to-liquids (GTL) diesel fuels produced by the Fischer-Tropsch process typically have very high cetane number and zero sulfur content and can provide reductions in particulate and NOx emissions [1]. ConocoPhillips is developing a demonstration scale plant in Ponca City, OK to produce GTL diesel. The present study is part of an Ultra Clean Fuels project entitled "Ultra Clean Fuels from Natural Gas," sponsored by U.S. Department of Energy under Cooperative Agreement No. DE-FC26-01NT41098.

In this paper, we present results from in-cylinder imaging in a Cummins 5.9L, turbocharged, six-cylinder, 4-stroke direct injection (DI) diesel engine using an engine videoscope system. The imaging studies provide a comparison of the fuel injection timing, ignition timing, spray formation and flame luminosity between different fuels. Results are presented for an ultra low sulfur diesel fuel with 15 ppm sulfur content ("BP15") and for a GTL diesel fuel produced by ConocoPhillips. Also, we present experimental results on combustion and emissions with this ConocoPhillips Fischer-Tropsch diesel fuel (COP F-T diesel), in comparison with an ultra low sulfur diesel fuel. Together, these results show the potential impact of GTL diesel fuel on injection, combustion, and emissions formation in diesel engines.

Experimental

Two different experimental systems were used in the work described here: a highly instrumented 6-cylinder DI turbodiesel engine equipped with an in-cylinder visualization capability and a highly instrumented, single-cylinder DI diesel engine equipped with in-cylinder and fuel injector sensors.

In-Cylinder Imaging. Tests were performed with a Cummins ISB 5.9L turbodiesel engine (MY2000, 235 HP max output) connected to a 250 HP capacity, eddy current absorbing dynamometer. The engine has been heavily instrumented, with a 0.1 crank angle resolution crank shaft encoder, a cylinder pressure sensor, a needle lift sensor and in-cylinder visualization using an AVL 513D Engine Videoscope. The engine and dynamometer are operated through an automated control system. Results are presented at an engine setting of 1800 rpm and 10% load.

Injection Timing and Heat Release Analysis. The single-cylinder engine tests were performed in a Yanmar L70 EE air-cooled, 4-stroke, single cylinder, DI diesel engine with a maximum power output of 7 hp was operated at 25% and 75% load and 3600 RPM (two operating modes from the G2 test from the ISO 8178-4.2 [2]). Cylinder pressure and fuel-line pressures were measured using Kistler piezoelectric pressure transducer models 6052B1 and 601B1, respectively. A Hall-effect proximity sensor, installed by Wolff Controls Corporation, was used to measure needle-lift in the injector. An AVL 364 shaft encoder installed on the engine crankshaft, along with a Keithley DAS 1800 data acquisition board enabled 0.1 CA degree resolutions of these signals. NOx emissions were measured using an Eco-Physics NOx analyzer integral in an AVL GEM 110 emissions bench.

Results and Discussion

In-Cylinder Imaging. Results from the in-cylinder imaging are shown in Figures 1 and 2. The figures compare the structure of the spray and flame for the BP15 and COP F-T diesel fuels at the same point in time after the start of injection (SOI), shown in terms of crank angle degrees after SOI. In the Cummins ISB engine it was observed that the BP15 fuel was injected at 0.2 crank angle degrees earlier than the COP F-T diesel, so comparisons are made relative to SOI. Also, each figure shows two views of each spray or flame. The viewing angle and orientation of the videoscope camera probe can provide different perspectives on the injection and combustion processes. In both Figures 1 and 2, a close-up view of the spray provides a clear view of the spreading angle and both the start and end of injection, while a view from a greater distance can provide an image of the entire length of the spray showing differences in penetration into the combustion chamber. Figure 1 shows images at 4 crank angle degrees after SOI (ASOI). Figure 2 shows images at 10 crank angle degrees ASOI. In both sets of images, Figure 1 showing the spray prior to ignition and Figure 2 showing flame structure well after ignition, there are no significant differences in the general structure of the spray or flame that are visible in this qualitative comparison, despite the significant differences in fuel properties.

Injection Timing and Heat Release Analysis. With the engine set at 25% load, Figures 3 and 4 compare injection timing and heat release results at two injection timing settings, set using shims between the fuel injection pump and the cylinder block. For the ultra low sulfur diesel fuel, BP15, combustion is delayed as injection is delayed leading to degraded combustion, which is particularly evident at the retarded injection timing. The higher cetane number of the COP F-T diesel causes the F-T diesel blend to perform well despite retarded injection timing, as seen for the late injection timing in Figure 4. As Figure 5 shows for the "late" static fuel injection timing, the differences in the heat release rate are not as significant at higher load where the ultra low sulfur fuel does not display degraded combustion as it does at the light load. Nonetheless substantial differences in emissions and fuel consumption are observed between the test fuels as injection timing and load are varied. Figure 6 presents brake specific fuel consumption, NOx emissions and CO emissions at 25% load for the "early" and "late" fuel injection timings. At the late injection timing, CO emissions increase and fuel consumption increases for the ultra low sulfur diesel fuel relative to the COP F-T diesel. NOx emissions are observed to have a more complex trend with fuel type. NOx decreases with retardation of injection timing, as expected. But, at light load NOx emissions are slightly lower for the ultra low sulfur diesel fuel than for the F-T diesel. However, the lower NOx with the ultra low sulfur diesel fuel at light load and retarded injection timing is at the substantial expense of CO and fuel consumption. At the higher load setting, NOx, CO and fuel consumption are always lower for the COP F-T diesel fuel.

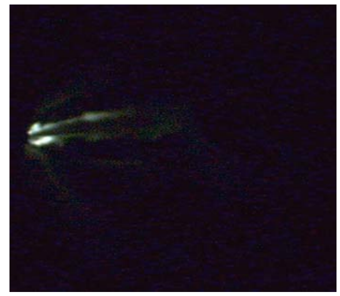
Angles	BP15	FT100
Endo-scope 60 / Illumi-nation 70		
Endo-scope 30 / Illumi-nation 30		

Figure 1. Videoscope images of injection of BP15 and COP F-T diesel within Cummins ISB 5.9L turbodiesel engine at 4 degrees ASOI.

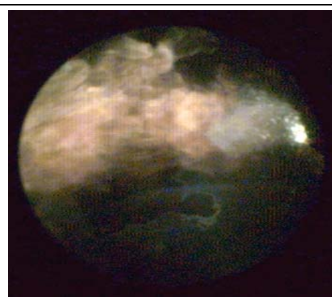
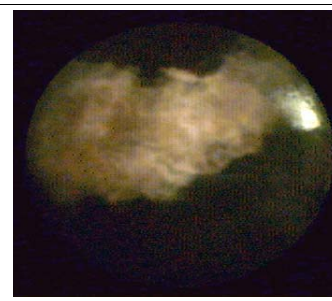
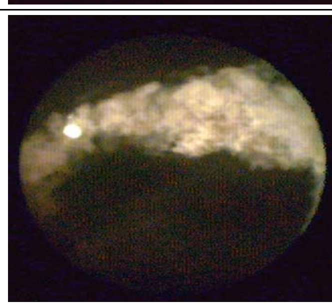
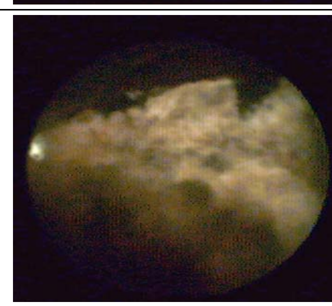
Angles	BP15	FT100
Endo-scope 60 / Illumi-nation 70		
Endo-scope 30 / Illumi-nation 30		

Figure 2. Videoscope images of injection of BP15 and COP F-T diesel within Cummins ISB 5.9L turbodiesel engine at 10 degrees ASOI.

Conclusions

While in-cylinder imaging comparisons of ultra low sulfur diesel fuel and synthetic diesel fuel show no significant differences in spray or flame structure, injection timing and heat release analysis show that the high cetane number and low bulk modulus of compressibility of the F-T diesel fuel lead to significant differences in heat release and pollutant formation.

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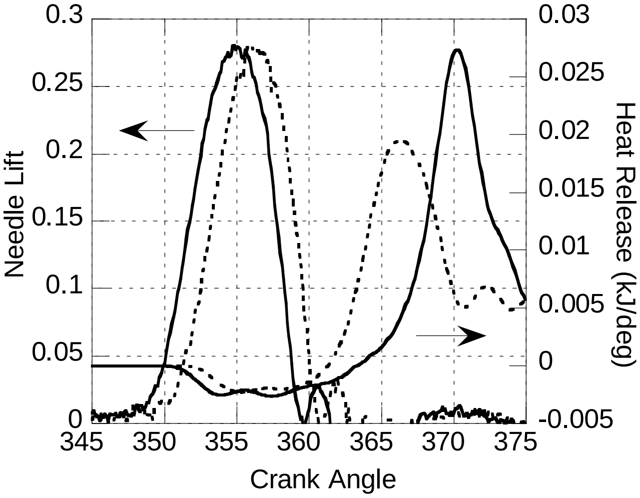

Figure 3. Needle lift and heat release versus crank angle for the "early" static injection timing at 25% load and 3600 rpm, in a Yanmar L70 DI diesel engine. (—) BP15 ultra low sulfur diesel fuel and (- - -) COP Fischer-Tropsch diesel fuel.

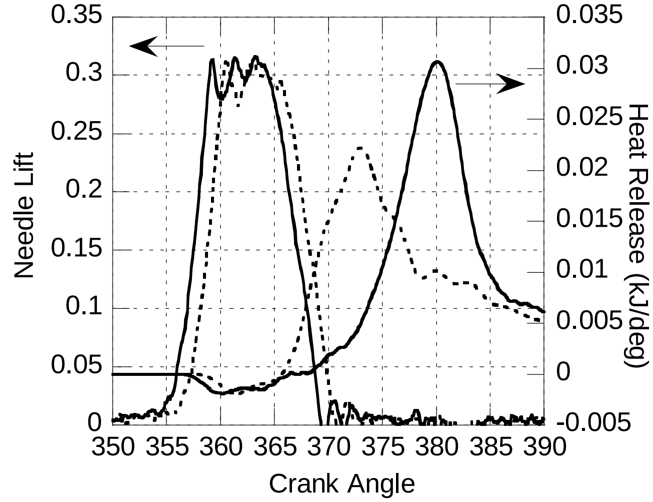

Figure 5. Needle lift and heat release versus crank angle for the "late" static injection timing at 75% load and 3600 rpm, in a Yanmar L70 DI diesel engine. (—) BP15 ultra low sulfur diesel fuel and (- - -) COP Fischer-Tropsch diesel fuel.

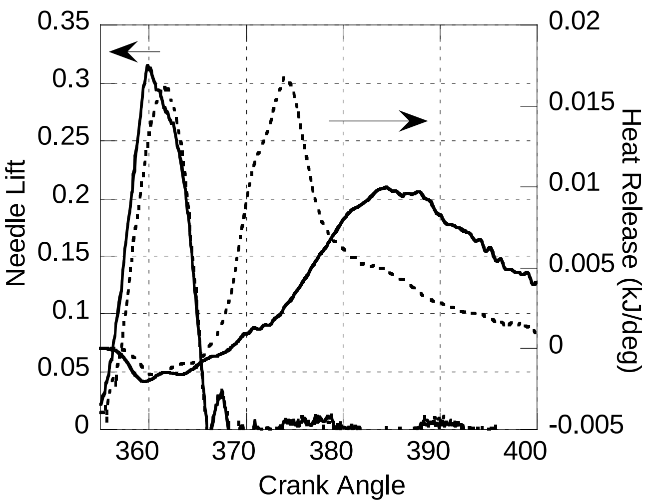

Figure 4. Needle lift and heat release versus crank angle for the "late" static injection timing at 25% load and 3600 rpm, in a Yanmar L70 DI diesel engine. (—) BP15 ultra low sulfur diesel fuel and (- - -) COP Fischer-Tropsch diesel fuel.

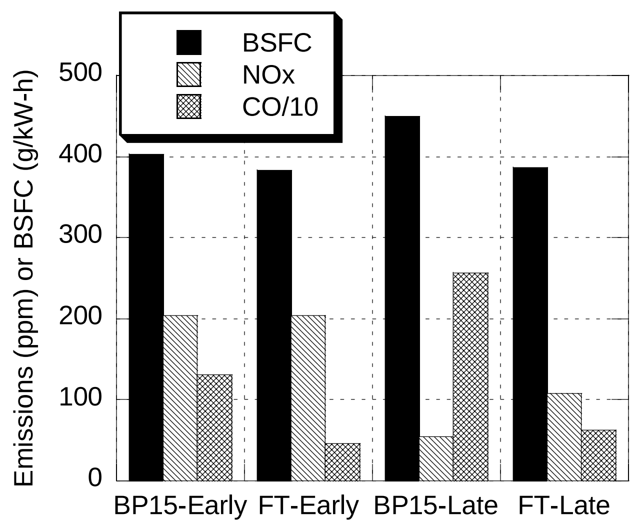

Figure 6. Brake specific fuel consumption, NOx emissions and CO emissions for BP-15 and COP F-T diesel fuels at 25% load and 3600 rpm, at the "early" and "late" injection timing settings.

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References

(1) Lloyd, A.C. and Cackette, T.A., *J. Air & Waste Manage. Assoc.*, **2001**, *51*, 809-847.

(2) International Organization for Standardization, ISO 8178: Reciprocating internal combustion engines - Exhaust emissions measurement - Part 4. Test Cycles for different engine applications. 1995.